3.0. AIRBORNE NAVIGATION SYSTEMS TESTING

3.1. INTRODUCTION TO NAVIGATION THEORY

3.1.1. General

The purpose of any airborne navigation system is to determine aircraft position, velocity and orientation relative to a specified reference point, using some coordinate system optimized for use on the host platform. For most airborne navigation systems, the preferred reference point is fixed at the center of the earth. The earth center reference point is moving around the sun which is in turn moving fairly linearly through space. By fixing the reference point to the center of the earth, these motions can be ignored, leaving only motion of the point on the earth's surface at which the aircraft is located relative to the earth's center (the only significant factor is earth rotation for the mission durations of airborne systems) and movement of the aircraft across the earth's surface.

The coordinate system of most use in airborne applications is a spherical system using latitude, longitude and altitude. Due to system limitations, many electronic navigation systems actually operate referenced to a point on the earth (for instance the position of an electronic navigation aid ground station) and using a cylindrical coordinate system of bearing, range and altitude centered at the point. [Ref. 38:p. 1.1]. In some cases, such as in long range, great circle navigation, the pilot is best able to orient in spherical coordinates (latitude, longitude and altitude). In other cases, for instance during an ingress and attack of a surface target, the pilot is best able to orient in a cylindrical format (bearing, range and altitude) referenced to the position of the target. Often a conversion can be made, which may be transparent to the operator, between the two coordinate systems.

Navigation systems can be divided into the broad categories of position fixing and Dead Reckoning (DR) navigation systems. In position fixing, the system determines the location of the host aircraft at a discrete point in time. Position fixing systems tend to be very accurate, compared to DR systems, at the time the location is measured but will drift in accuracy in the short term as the host aircraft moves between fixes. Long term accuracy is good since the position is updated at intervals. DR systems continuously estimate position as the host aircraft moves within the coordinate system by integrating platform acceleration and/or velocity to obtain the change in coordinate values and then adding them to the initial position coordinate values. DR systems tend to have good short term accuracy following the initial fix; however, the long term accuracy degrades as errors accumulate since the reference position is not updated. [Ref. 38:p. 1.3]. The strengths of both systems can be exploited by combining a position fixing and DR system into a single integrated navigation system. A DR system is used to provide optimum short term accuracy while the position fixing system provides periodic position updates for the best long term accuracy. [Ref. 38:p. 1.2].

A variety of DR systems are used in modern aircraft. The most common are Inertial Navigation Systems (INSs) and Doppler Navigation Systems. A larger number of position fixing systems are available, including Tactical Air Navigation (TACAN), VHF Omnidirectional Ranging with Distance Measuring Equipment (VOR/DME), Long Range Navigation (LORAN), OMEGA and the satellite based Global Positioning System (GPS). These systems are tested in essentially the same manner, using the same basic techniques. To illustrate the DR, position fixing and fully integrated position fixing/DR test techniques, two sample systems will be used. The first system is a semi-analytic, north seeking INS, augmented with a visual, radar, OMEGA and TACAN update mode. The combining and coupling of the position fixing and DR systems is minimal, and so the test techniques are developed as essentially stand-alone DR and position fixing routines. The second system is a fully integrated GPS/INS. It will be seen that the test procedure is an adaptation of the tests developed for the stand-alone DR and position fixing systems.

In order to limit confusion between the discussion of the two sample systems, treatment of the second system will be delayed until after the presentation of the OMEGA tests. This will be a minor departure from the format of the radar and electro-optical sections, where all the system theory is provided at the beginning of the chapter, but it will enhance readability. A single exception is the Preflight and Built in Tests procedures.

3.1.2. Inertial Navigation Systems

3.1.2.1. Components

INSs are composed of two basic components, gyroscopes and linear accelerometers. Linear accelerometers are used to measure acceleration along the axis in which the device is oriented. [Ref. 38:p. 2.10]. If the linear accelerometer is accelerated in a direction not aligned along the axis of orientation, it will measure the vector component of the acceleration along the axis of orientation. In airborne INS systems, at least three orthogonally aligned accelerometers are used and the measured acceleration of the three are vectorially added to gain the actual acceleration vector value. There are two types of gyroscopes. Position gyroscopes measure rotational displacement of the gyroscope case (which is usually attached to the airborne host platform) around the input axis as measured from some initial position. Rate gyroscopes measure the rotational rate of the gyroscope case around the input axis. Both types of gyroscopes rely on "the fact that a rotating (spinning) element tends to maintain its spin axis in a direction fixed with respect to inertial space". [Ref. 38:p.2.12]. Inertial space is referenced to a fictional point that is not moving relative to all matter in the universe.

3.1.2.2. Analytic/Semi-Analytic and North Pointing/Wander Azimuth Systems

In most INSs the gyroscopes (whether displacement or rate gyroscopes) are used for one of two purposes. In the analytic system, the frame of reference is stabilized in inertial space. [Ref. 38:p.2.6]. In this case, the three-dimensional coordinate system remains fixed in space and as the earth rotates, the earth revolves around the sun, and the host platform moves across the earth, the three reference planes appear to rotate when compared to local vertical and the true north direction. The gyroscopes measure the host airplane orientation in inertial space, the accelerometers measure all acceleration relative to inertial space and the results are manipulated mathematically to determine accelerations actually due to movements across the earth's surface and due to changes in altitude above the earth. This process is extremely complicated and computer intensive and so most INSs use a semi-analytic system in which the gyroscopes are used to orient the accelerometer array, and thus the local horizontal reference plane, perpendicular to local vertical for the host platform's position on the earth. This leaves one reference plane perpendicular to local vertical and the altitude axis coincident to local vertical. The plane perpendicular to the local vertical is known as the platform. Continuous correction of the platform orientation as the earth rotates and the host aircraft moves over the surface of the earth is required but this method allows for mathematical corrections for the gravitational vector to be added in a single axis and for measurements of movement across the face of the globe to be made directly in two dimensions. [Ref. 38:p. 2.17].

In the case of a north pointing, semi-analytic system, not only is the platform maintained relative to local vertical but one of the two axes defining the plane is always oriented to true north, allowing for direct measurement of displacement in latitude, longitude and altitude. Wander azimuth systems do not physically maintain the alignment of the platform with the true north reference but use the output of the gyroscopes to maintain track of where true north is located. The output of the accelerometers located in the reference plane are then vectorially resolved into north-south (latitude) and east-west (longitude) components. This process uses more computer computations but does not require continuous alignment of the platform accelerometers with true north. A semi-analytic, wander azimuth type INS will be used as the sample system for development of the test techniques to be presented later.

3.1.2.3. Vertical Tracker

The vertical tracker portion of the semi-analytic INS is designed to maintain the INS platform orientation orthogonal to the local vertical. The clearest way to envision this is to imagine a cable stretched from the center of the earth to the host aircraft INS. By aligning the INS platform relative to the cable as the host aircraft moves across the face of the earth, the correct orientation can be maintained. This is equivalent to attaching the host aircraft to the end of a pendulum of length equal to the radius of the earth. This is known as a

Schuler pendulum, which has a period of 84.4 minutes. [Ref. 38:pp. 2.19-2.21]. An equivalent Schuler pendulum can be mathematically modeled within the INS computer and combined with a mathematical model of the earth's rotation rate and host aircraft latitude and altitude to calculate the direction of the local gravity vector. The platform is then physically aligned perpendicular to this calculated gravity vector.

Two additional platform corrections are required for an INS moving across the earth's surface. As the INS moves in an east-west direction, the effective rotation rate of the local vertical due to the earth's rotation must be decreased for a westerly velocity and increased for an easterly velocity. In addition, as the INS is moved in a north-south direction, the distance to the earth's center of rotation changes. The Coriolis force then causes an easterly acceleration for north velocities and a westerly acceleration for a southern velocity. These corrections must be calculated within the INS computer and the corrections accounted for, or the local gravity vector, and thus the platform alignment and the north-south and east-west accelerations, will be incorrect. [Ref. 38:pp. 2.21-2.22].

The Schuler pendulum has an interesting effect upon the output of the INS as errors are induced on the vertical tracker. As the orientation of the platform is tilted from the exact local vertical, the gravity vector will be sensed in the horizontal channel. The acceleration error due to gravity is cyclic and has a period of 84.4 minutes and is known as a Schuler cycle. The Schuler cycle is characteristically undamped and so many INSs will use an independent input (often a velocity input from a source such as a doppler navigation system) to damp out the Schuler oscillations and to correct the vertical axis error. [Ref. 38:pp.2.24-2.25].

Much has been said about the local gravity vector without actually defining its value. The local acceleration due to gravity can vary in magnitude due to both host aircraft altitude and local anomalies and in direction due to the fact that the earth is not exactly round but a non-homogeneous, oblate spheroid. The actual value can be modeled by a complicated expression including as much as thirty-two terms; however, most INSs use a much simpler model and rely upon periodic updates to correct the resultant inaccuracies. Local gravitational anomalies can cause as much as a one nm/hour error in INS derived velocities. [Ref. 38:pp. 2.9,2.26].

3.1.2.4. The Vertical Channel

The vertical channel of the INS is unstable. This results from the fact that the local gravity vector decreases in magnitude as the altitude above the center of the earth increases. When the second derivative of the vertical acceleration is taken to determine the vertical axis positional change (altitude change) a negative value of the zero derivative gravitational change correction for altitude must be added. The resulting second order relationship is unstable. Methods exist for providing the feedback necessary to damp this phenomenon and to provide better altitude and vertical velocity determination; however, sufficient altitude accuracy is achievable by much cheaper and simpler methods and so most tactical aircraft INSs do not use the vertical INS channel. [Ref. 38:p. 2.27-2.28]. The sample system to be used for the development of the test techniques to follow will not use a vertical channel.

3.1.2.5. The Horizontal Channel

Understanding the vertical seeker and the vertical channel, the horizontal channel can now be described. Starting with a level platform, the INS accelerometers measure acceleration perpendicular to the local vertical. The INS calculates and adds corrections for the coriolis effects, centrifugal acceleration (due to earth rotation) and local acceleration due to gravity including aberrations/altitude corrections. The sum is then integrated to get rates. The rates are then sent back as input to the vertical seeker feedback loop and then integrated again to get the change in position. The change is added to the original position to get the new position. [Ref. 38:p. 2.26a].

3.1.2.6. Initialization and Alignment of the INS

Since the INS is a DR type navigation system, it must have an initial position and orientation from which to navigate. For the semi-analytic, north seeking INS, the level platform and initial true north reference must be established before navigating from the initial latitude-longitude position. The process is performed in two stages, platform leveling and gyrocompassing, which may be performed concurrently for at least a part of the process. Platform leveling is the process by which the platform is physically oriented perpendicular to the local vertical. Gyrocompassing is the process by which the semi-analytic platform reference is aligned with true north. [Ref. 38:p. 2.36-2.37].

After the present latitude and longitude of the INS is entered into the INS computer, the process begins with coarse leveling, where the platform gimbals are aligned with preset angles with respect to the host aircraft. Next, the north azimuth of the platform axis is rotated to an alignment with north as provided by the aircraft magnetic compass. At this point, the coarse leveling and alignment process is complete and a feedback process is begun to refine the leveling and alignment process.

In the fine leveling process the gravity vector is used as the feedback input. With the platform out of level, a component of gravity is sensed in the platform plane. The platform is torqued to null out this acceleration. The errors tend to be very small; however, and usually a few minutes are required to sufficiently null out the error. [Ref. 38:p. 2.37-2.38]. For fine gyrocompassing, as the earth rotates, the platform is torqued to maintain the orientation perpendicular to local gravity (as explained earlier). This torquing is performed based upon knowledge of the orientation of true north. An error in the true north reference will cause the platform to be torqued around the incorrect axis, will result in the acceleration due to gravity being sensed in the platform and can in turn be used as an error signal similar to the fine leveling process described above. [Ref. 33:p. 35-36]. The process can take up to 10 minutes in many systems.

As is obvious from the description of the leveling process, the direction of local vertical must be known precisely to perform the procedure. In addition, the direction of true north relative to the erroneous axis about which the platform is torqued during the gyrocompassing process must remain fairly constant over long periods for the process to be performed. For this reason, the INS alignment and initialization process is usually performed while the aircraft is being started and before aircraft taxi. If the aircraft must be moved before the alignment and initialization is complete, the process must be suspended and then re-initiated when the aircraft is no longer moving. Using this technique fixes the local vertical vector relative to the aircraft (assuming the aircraft is on a level surface) and provides a steady true north reference between aircraft moves. This is by far, the simplest and most accurate method.

Ship-based aircraft pose a particularly difficult problem since their position changes, as does aircraft attitude relative to local vertical, as the ship pitches, rolls, yaws and moves across the earth. These aircraft INSs require a complicated, continuous input of the ship position and orientation parameters while the alignment is performed. This method requires special hardware and more alignment and initialization time than shore based methods.

Although much less accurate and much more time consuming, an alignment and initialization can usually be performed while airborne. An airborne alignment may be required due to an airborne system failure or following a rapid alert type launch where ground initialization and alignment may not be allowed due to time constraints. Airborne alignment and initialization usually requires an outside source of reference velocity (such as a doppler radar system), a source of precise aircraft position and long periods of straight and level flight. The results of airborne alignments are almost always much less accurate than the shore or ship based alignments.

While the alignment is taking place, the operator is usually provided with a status indicator of the alignment stage and thus a feel for how much longer the alignment will take. This status indicator and subsequent alignment complete indicator is essential since the long period required for INS alignment is often the limiting factor in aircraft alert response. A typical method is to provide a countdown of numbers with alignment complete indicated by a zero. In addition, fault discretes are provided to indicate various states of INS operation as well as BIT detected faults.

3.1.2.7. Inertial Navigation System Augmentation

An augmented INS uses some outside source to update some number of INS parameters following the initial alignment. To completely initialize the system and null out all errors and drift rates; all position, velocity and platform orientation parameters would have to be updated simultaneously and precisely. A full update is rarely possible in a tactical system. Most update only the aircraft position. The effect is to zero out position errors, leaving the error drift rate as it was before the update. [Ref. 38:p. 2.40].

The sample INS system, to be used for the remainder of the discussion, is augmented by visual flyover, radar, TACAN and OMEGA updates. In flyover updates, the pilot identifies a visual point of known latitude and longitude (which is entered into the INS computer) such as a surveyed tower. The pilot then flies over the point, visually marks on top, and commands an update. The INS position then changes to the entered latitude and longitude and navigation begins as before from the new latitude and longitude. In the radar update method, a radar target of known latitude and longitude is identified and entered into the INS computer. The radar cursors are then used to designate the point on the radar screen and this radar derived position, offset by the radar bearing and range, is used to re-initialize the INS position in a manner similar to the visual flyover. In the TACAN update, the TACAN bearing/range and known TACAN position are used in a manner similar to the radar update to re-initialize the INS position. Finally, in an OMEGA update, the OMEGA latitude and longitude are used as a direct replacement for the INS latitude and longitude. In all of these cases the drift rates that contributed to the initial errors are typically still present, requiring further updates.

3.1.2.8. Characteristic INS Errors

A list of INS error sources are provided below. Some of these errors are constant, some increase with time (linearly, exponentially, etc.) and some oscillate at the Schuler cycle frequency (84.4 minute cycles) or at the earth rate frequency (24 hour cycles). [Ref. 38:p. 3.3-3.5].

<u>Gyroscope Errors</u>
Accelerometer Error Output
Drift Rate
Output Bias
Torquing Error
Scale Factor Error
Nonlinearity
Misalignment

<u>Gimballed-Platform Error</u>
Acceleration-Induced Error
Structural Misalignment
Mass Unbalance
Vehicle Motion Isolation Inadequacies

<u>Accelerometer Errors</u>
Output Bias
Scale Factor Errors
Cross-Acceleration Errors
Nonlinearity
Misalignment

<u>Computer and Software</u>
Gravity Model Errors
Sensor Compensation Error
Analog to Digital Conversion Errors
Truncation and Round-off Error
Computational Algorithm Approximations

<u>Initialization, Update, Gyro-compassing and Damping Errors</u>
Position and Velocity Errors
Platform Alignment Errors

All of these errors are statistically uncorrelated [Ref. 38:p. 3.5] and when enough significant sources of error are present for an individual INS, the sources and their contribution to the total error cannot easily be determined. Sometimes a few sources are dominant and the individual sources can be identified by their characteristic error plots. Four are of particular importance because of their magnitude and the frequency with which they occur.

As was noted earlier, a platform leveling error will excite a cyclic error that oscillates at the Schuler cycle period. For a misalignment about the east-west axis, a north position error will be noted (latitude). For a misalignment about the north-south axis, an east position error will be noted (longitude). [Ref. 38:p. 3.5a]. For a constant platform leveling error, the maximum error will remain constant. As the leveling errors increase, so will the maximum error excursions in position. An initial error in aircraft latitude position will cause an oscillation in the north-south position error at the earth rate, with a 24 hour period. [Ref. 38:p. 3.5b]. An initial error in the true north reference, whether in a north seeking or wander azimuth system, will cause a combined effect. An oscillatory error will occur at the earth rate with a 24 hour period; however, the oscillation will be about a linearly increasing average error. The magnitude of the oscillation and the slope of the linearly increasing "zero point" of the oscillation will depend upon the magnitude of the north reference error. [Ref. 38:p. 3.5c] Finally, the INS azimuth gyro will tend to drift from the initial true north reference resulting in a north position error. This effect is characterized by a non-linear error of increasing slope. [Ref. 38:p. 3.5d].

3.1.3. OMEGA

3.1.3.1. Theory

OMEGA is a radio navigation, position fixing system, that compares the Very Low Frequency (VLF) signals from pairs of ground stations to determine an ambiguous [Ref. 64:p.1] range difference between pairs. There are eight stations as described below in table III [Ref. 64:p.1]:

The VLF frequencies used by the OMEGA system range between 9 and 14 Kilohertz (KHZ). Figure 8 depicts the transmission pattern of the station signals. The patterns repeat every 10 seconds. The individual station location is depicted to the left, the pulse widths and transmission gap widths are above the depiction of the trains in units of seconds and the frequency of each pulse is beneath the depiction of the pulses and are provided in units of KHZ. [Ref. 64:p.7].

The transmission pattern of the individual stations are very precisely synchronized using cesium standard clocks. [Ref. 64:p.2]. It is this highly precise, synchronized time that enables OMEGA to operate. In addition to being synchronized in time, the transmitted signals are also synchronized in phase. When an OMEGA receiver picks up two OMEGA signals transmitted at the same frequencies they are saved and compared to determine the phase relationship. The pairs of stations chosen for this comparison are generally those for which the OMEGA receiver lies as close as possible to a line drawn between the two stations (baseline). Figure 9 shows how position is determined for the very simple case of two stations separated by a baseline length of 1/2 wavelength.

Table III: OMEGA GROUND STATIONS

Station	Letter Designation	Coordinates
Norway	A	66° 25′ 12.62" N 013° 08′ 12.52" E
Liberia	B	06° 18′ 19.11" N 010° 39′ 52.40" W
USA: Oahu, Hawaii	C	21° 24′ 16.78" N 157° 49′ 51.51" W
USA: La Moure, North Dakota	D	46° 21′ 57.29" N 098° 20′ 08.77" W
France: La Reunion	E	20° 58′ 27.03" S 055° 17′ 23.07" E
Argentina	F	43° 03′ 12.89" S 065° 11′ 27.36" W
Australia	G	38° 28′ 52.53" S 146° 56′ 06.51" E
Japan	H	34° 36′ 52.93" N 129° 27′ 12.57" E

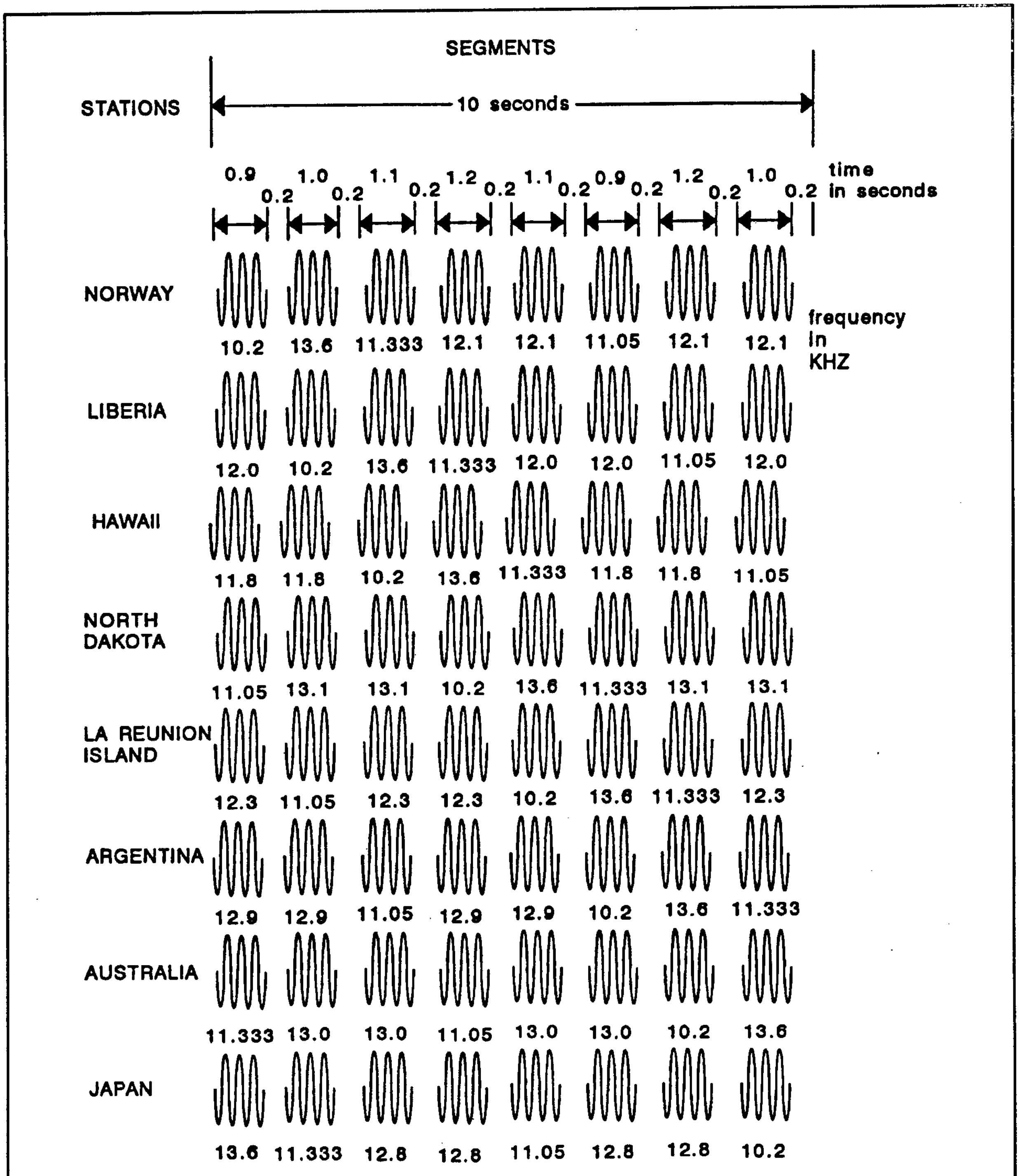

Figure 8: OMEGA Transmission Format [Ref. 27:p.7]

Since the velocity of propagation is relatively constant and the wavelength for a given frequency is known, the distance between stations, along the baseline, can be found from the phase of the signal at that point; again, for the simple case where the transmitters are separated by 1/2 wavelength. If the difference in phase is found, a locus of points, describing a hyperbola, are defined where the difference in phase between the signals is a constant. OMEGA is thus a hyperbolic navigation system.

In reality, the wavelength of the signals is only 16 nm (at the 10.2 KHZ frequency) and the stations are actually

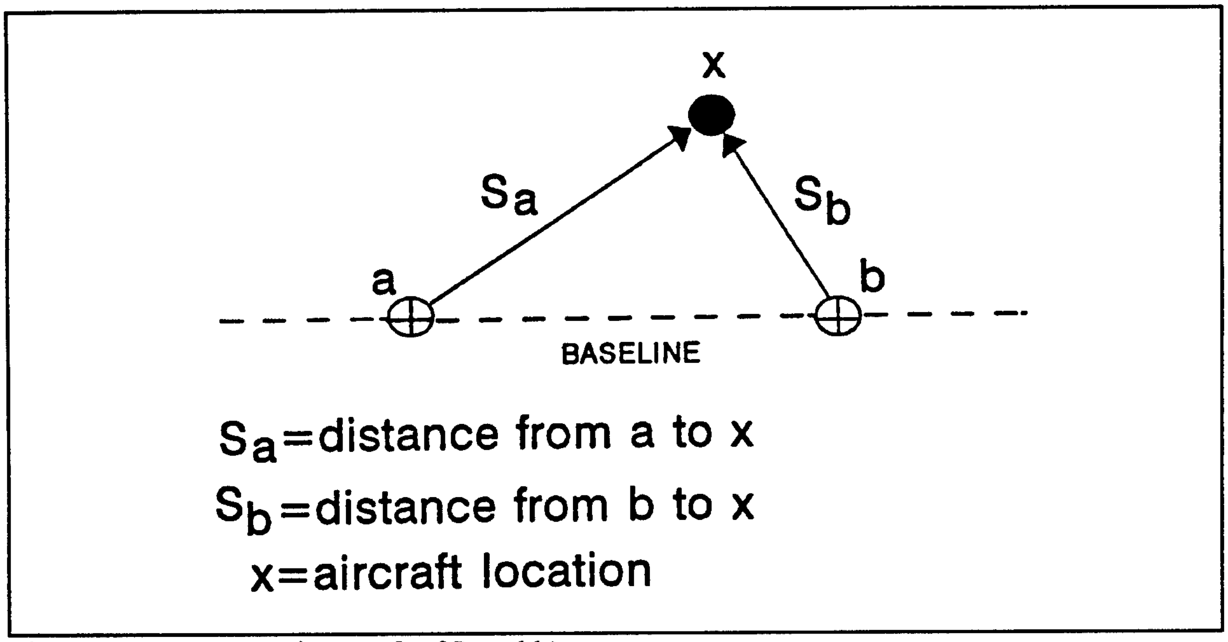

Figure 9: OMEGA Fix [Ref. 27:p.11]

separated by thousands of miles. This means that the hyperbolic loci of points are ambiguous at each 1/2 wavelength for the frequency used. [Ref. 64:p. 11]. The area between the zero phase difference (every 180° of phase shift) hyperbolic curves for each station pair are called lanes. The distance between lanes expands as the loci move away from the baseline. [Ref. 64:p.13]. The effects of the ambiguity can be partially mitigated by analyzing the phase difference of several of the frequencies transmitted by the same pair of stations. Analysis of the beat frequencies allows the use of lanes that are ambiguous at approximately every 144 miles. The exact width depends upon the wavelengths in question. [Ref. 64:p. 13-17].

Since some degree of ambiguity exists in either case, some method is required to determine the correct lane. Commonly, the technique used is to initialize the system at a beginning position (generally a latitude and longitude) and then to simply count the crossings of the zero phase difference points that define the lane edges. [Ref. 64:p. 13]. This function is automatic in airborne OMEGAs and is usually accomplished by keeping track of the OMEGA derived position and dead reckoning between fixes. In this way, the position of the aircraft is known along a unique hyperbolic curve that crosses perpendicular to the baseline between the stations. By repeating the procedure for two pairs of stations, the crossing of the two hyperbolic lines can be used to define a fix. [Ref. 64:p.14]. Note that it is entirely possible to have two hyperbolas cross at two distinct points. This ambiguity can be solved by comparing the two positions to the approximate position used to keep track of lane ambiguities.

3.1.3.2. Accuracy

As was mentioned, the lane hyperbolas are perpendicular to the line connecting the stations in use (baseline) and due to their shape, separate as they move away from the baseline. Since the accuracy with which the phase shift can be measured is the same at the baseline as away from it, the band of accuracy of the hyperbola upon which the OMEGA can locate the aircraft expands as the aircraft moves off the baseline. This phenomenon is called Geometric Dilution Of Precision (GDOP). Luckily, the extremely long baselines used in the OMEGA system mitigate the GDOP effects greatly as long as the optimum ground stations are chosen.

One reason the VLF frequency range was chosen for OMEGA was the extremely long transmission ranges possible in this frequency band. When VLF waves are transmitted they tend to bounce off the bottom of the ionosphere and off the earth's surface. The effect is to duct the waves around the earth. Because of this, the characteristics of the two ducting surfaces can affect the OMEGA RF and thus the accuracy of the system. Generally, the propagation characteristics are fairly predictable; however, several perturbations can affect the transmission and must be accounted for. First, the altitude of the ionosphere is quite different between day and night. The night altitude is somewhat less predictable than the day altitude, accounting for a slight degradation in the night time OMEGA accuracy; however, both altitudes can be approximately accounted for in the programming of an automated OMEGA system. This phenomenon is known as the diurnal effect. Second, the transition line between night and day causes instabilities in the propagation pattern due to the changes between the day and night ionospheres. This effect can be mitigated through preference to station pairs that do not have a baseline currently intersecting the transition line and when still needed, by partial correction within the OMEGA software. [Ref. 64:pp. 17-18]. Third, variations in the transmission over different surfaces can affect propagation. Smooth water is a near perfect ducting surface while large ice masses at the polar caps can make the signal nearly unusable. The solution is to compensate for the propagation effects knowing the point of origin of the RF, the position of the aircraft and the terrain between. Since polar cap attenuation is so pervasive, stations providing directions of arrival over the poles are usually deselected. [Ref. 32:p. 1-30].

When the RF is radiated from the large OMEGA groundsite antennas, three paths, or modes, are possible. The first is the direct path between the station and the aircraft, the second immediately bounces off the ionosphere and then propagates to the aircraft and the third bounces off the ground and then propagates to the aircraft. The three modes can then interfere with each other. Fortunately, the skywave and groundwave RF are rapidly attenuated with the net effect that the interference is only a significant factor from minimum range to approximately 200 to 500 nm from the groundsite. The phenomenon is known as near station modal interference and is countered by simply deselecting the closer stations. [Ref. 11:p. 7]. Since VLF has excellent long range propagation characteristics, it is quite possible for the aircraft to receive RF from a groundstation via the long route around the earth as well as the direct route. The two signals then interfere with each other. The interference is rare when the station is within 8,500 nm of the aircraft; however, and so the problem is minimized by deselecting stations at very long ranges. [Ref. 32:p. 1-62].

The next two phenomenon to be discussed are Sudden Ionospheric Disturbances (SIDs) which are caused by X-rays emitted during solar flares, and Polar Cap Anomalies (PCAs) which are present only at high latitudes and result from high energy protons emitted from the sun that are drawn to the poles by the earth's magnetic field. These two phenomenon cannot be accurately predicted and thus cannot be accounted for within the OMEGA system. These errors can amount to as much as 8nm at the 10.2 KHZ frequency. [Ref. 64:p. 19]. These two effects are of short duration and rarely are a significant factor.

The final effect to be discussed here is caused by the relatively long integration period of the OMEGA system, that is, the time required for the OMEGA to update the position. The airborne OMEGA can require as much as two minutes to update the displayed position and as such usually requires dead reckoning between fixes. The OMEGA is then prone to the errors inherent in any DR system. [Ref. 38: p. 2.81]. Excluding the unpredictable SID, PCA and DR errors, the day time accuracy of the modern OMEGA system with automatic latitude and longitude determination/display and automatically applied correction tables is around 1 nm in the daytime and 2 nm at night [Ref. 38:2.82].

3.1.4. Tactical Air Navigation

3.1.4.1. Theory

TACAN provides relative, magnetic bearing and slant range in nm to a known ground station. The systems used for bearing and range are separate. TACAN bearing is found by comparing the phase relationship of a rotating antenna pattern and omnidirectional reference pulses. The antenna pattern is transmitted at the ground site and is in the shape of a cardioid that has a nine lobed pattern superimposed upon it. The entire pattern rotates at 15 HZ and thus the rotating maximum of the cardioid will pass a given bearing at a rate of 15 HZ and one of the nine lobes will pass the same bearing at a rate of 135 HZ. Simultaneously, an omnidirectional pulse train is transmitted each time the maximum of the cardioid passes through east. A second pulse train is transmitted each time any of the nine maximums pass through east. The envelope of the two superimposed sinusoidal signals (15 and 125 KHZ) are resolved by the airborne receiver. The phase of the two signals are then compared to the reference signals transmitted at the east position. The phase difference will be zero for the 15 KHZ signal only if the receiver is east of the groundstation. The phase difference will increase from 0 to 360° as the receiver is moved around the ground site clockwise. The 15 KHZ signal will provide an unambiguous bearing; however, the bearing is fairly inaccurate. The 135 KHZ signal provides the required accuracy but is ambiguous every 40°.

Each time one of the nine maximums crosses east, the corresponding pulse train reference signal is transmitted. As the receiver moves around the ground station, the phase shift between the 135 KHZ envelope and the reference will shift through 360° every 40° of rotation around the ground station. The 15 KHZ rough bearing is used to resolve the 135 KHZ ambiguity. Occasionally, the ambiguity is solved incorrectly and the TACAN will provide a bearing in error by multiples of 40°. This is known as 40° lockout. For bearing, TACAN uses line of sight propagation in two bands from 962 to 1024 and 1151 to 1213 MHZ, a maximum power out from the ground site of 1 to 20 KW and a maximum range of 300 nm from the ground station to the receiver. Bearing error is usually around 3.5° and results from site errors associated with ground and other reflections of the signals transmitted by the ground site and from errors associated with the airborne receiver. [Ref. 38:pp. 2.68-2.74].

Range from the ground station to the TACAN equipped aircraft is derived by measuring the time for an interrogation pulse to travel from the aircraft to the TACAN ground station and for a reply to return to the aircraft. The hardware is called Distance Measuring Equipment (DME). The airborne TACAN transmits an interrogation pulse pair consisting of 3.5 μsec pulses 12 μsec apart and at a frequency separated by 63 MHZ from the ground station reply frequency. The ground site receives the interrogation, holds it for a fixed period of 50 μsec, and then sends out a reply. Subtracting the set delay period, range can be determined directly, given the speed of propagation. Each ground site can handle 100 simultaneous users. As the number of users increases above this number, the 100 interrogators with the strongest signals are serviced.

Since all the reply signals are identical, two techniques are used to prevent the display of ranges based upon replies to other TACAN interrogators. First, a range tracker is used within the airborne TACAN unit, that rejects replies out of the expected window. Since it is still possible to have some number of aircraft at the same approximate range from the ground site and thus crossing within each other's range gates, the interrogators vary the PRF between 5 and 25 Pulses Per Second (PPS) to reduce the chance that the incorrect replies will fall in the tracked range gates. Establishment of the initial range tracker gate and subsequently the display of the first DME value can take from 1 to 20 seconds. To facilitate the initialization process, the PRF of the interrogation is increased to 150 PPS until range tracking is established. For ranging, the TACAN uses line of site propagation of airborne and ground site frequencies in the band of 1025 to 1150 MHZ, a power of 50 to 2000 W for the airborne equipment and 1 to 20 KW for the ground sites, and a usable maximum range of from 50 to 300 nm. Ranging accuracies vary from 0.1 to 3.0 nm. By far the largest contributor of error is the user equipment. [Ref. 38:pp. 2.65-2.67].

3.1.5. Missions

Although not as critical for navigation testing as for radar testing, a good knowledge of the intended mission of the navigation system is required to develop a proper test technique. For example, a knowledge of the intended operating area is useful in selecting the correct operating modes for a test INS to insure that time is not wasted testing modes that are likely not to be used. Many INSs use a special operating mode above 70° of latitude and if the aircraft is not expected to be flown above this latitude it could be a waste of time and money to take anything other than a cursory look at this function.

A knowledge of the intended mission duration is essential for development of test scenarios. For DR and integrated navigation systems, the airborne tests should be performed for at least a period as long as the expected mission duration. This is to ensure that the DR system's drift does not exceed the maximum allowable limits, even at the end of the mission. Mission relatable maneuvers need to be performed to ensure that normal mission g levels, maneuvering rates and aircraft attitudes do not adversely affect navigation accuracy. These maneuvers can affect the stability of an INS platform, exceed the dynamic range of the INS accelerometers or cause the fuselage to mask the antenna for a radio navigation system.

A thorough mission knowledge is required to understand the accuracy requirements of the system. The requirements for a system that must drop ordnance at given geographic coordinates and a system required for long range, overwater navigation are quite different. As with the radar test techniques, the navigation test techniques to be presented here require knowledge of the intended mission, since they are based upon the premise of qualitative testing in a mission relatable scenario and quantifiable data to support this assessment. If mission relatable experience is not present on the test team, then extensive research is required.

3.1.6. Navigation System Human Factors

As in the radar human factors section, no attempt will be made to completely cover the topic of ergonomics. As with radar systems testing, navigation system controls and displays testing must be performed while seated at the DEP and wearing a full set of personal flight equipment. The procedure for finding the DEP is explained in the radar theory section. The anthropometric measurements and the flight gear worn by the evaluator must be recorded.

3.1.7. The Flyover Method

The flyover method will be used as the primary means for determining the aircraft's actual dynamic (airborne) position. This position will be used as truth data. The technique is simple and requires a minimum of instrumentation. Preflight planning is important to this technique. Prior to flying the test, the evaluator must choose a number of surveyed landmarks to be used as flyover points. The landmarks must be easily found from the air, which usually means that the object used must be large compared to other features in the area and isolated from other landmarks. For instance, isolated towers are good choices in most terrains. Isolated road intersections in desert or plain areas are adequate. Distinct points of land, large sea navigation aids such as spider buoys or light houses and small, well defined river inlets are useful when doing testing near the coastline. The landmark must be discrete, that is, the pilot must not have to figure out which part of the landmark to fly over. As an example, an island is generally too large to use as a flyover point; however, a point of land on the northern edge of the island may be adequate.

As important as finding and isolating the specific feature, is knowing the exact latitude and longitude of the point. The location must be known with an accuracy commensurate with the test technique. For the flyover technique, a latitude and longitude position with an accuracy of around 100 feet is sufficient. When choosing the points, the evaluator can search a TPC of the test area and choose landmarks as shown on the chart. The surveyed positions are then derived from the listing of vertical obstructions, reference 68. These surveyed positions are of adequate accuracy for the flyover technique.

Flying the technique requires the pilot to first find the landmark. Onboard sensors such as navigation or surface search radar, electro-optical systems, as well as the navigation system under test can be used. Prior to flyover, the pilot must acquire the landmark visually. The technique involves flying directly over the target and recording data. The exact data differs depending upon the system under test; although, the identification of the landmark and the displayed position provided by the navigation system under test at the time of overflight is always required. Optimally, the pilot should fly directly over the target; however, if unable, the direction to the target and the displacement at the time of Closest Point of Approach (CPA) should also be recorded. The accuracy of the method is affected by the technique of the pilot and the flyover altitude. Generally, for a pilot experienced in the technique, the accuracy will be about one half of the altitude above the target. An altitude of between 200 and 2000 feet above the landmark is typical. [Ref. 38:p. 4.5]. The technique is flown identically for both position fixing and DR navigation system testing.